

Probabilistic Modeling of Long-Term Mass Loads from a Covered Dry-Stack Tailings Facility¹

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Abstract: The Greens Creek Mine is an underground Zn/silver/lead/gold mine, lying partially within the Admiralty National Monument on northern Admiralty Island, Alaska. The mine is located approximately 18 miles southwest of the city of Juneau. The Greens Creek Mine began production in 1989. Mining was temporarily suspended from 1993 to July, 1996, but has continued to the present. The United States Forest Service recently completed an environmental review (EIS) of a planned expansion of the tailings facility submitted by Kennecott Greens Creek Mining Company. The quantity and quality of seepage from the tailings facility, and development of appropriate long-term water management strategies were key issues in the EIS. Three key alternatives considered in the EIS included:

- The proposed action would permit an increase in the size of the tailings disposal facility. Kennecott Greens Creek Mining Company (KGCMC) would continue its present method of generating whole tailings. The tailings would be placed without chemical or biological additives. After cessation of milling an engineered cover would be placed over the tailings to reduce the flux of water and oxygen into the tailings.
- Addition of carbonates to tailings to insure long-term neutral pH
- Addition of organic carbon to the pile to promote *in situ* sulfate reduction

A stochastic predictive model was developed to estimate long-term chemical mass loads that may be generated from the dry-stack tailings. The model utilized empirical water quality data and cover performance monitoring and modeling to simulate the long-term geochemistry and hydrology of the tailings.

¹ Paper presented at the 7th International Conference on Acid Rock Drainage (ICARD), March 26-30, 2006, St. Louis MO. R.I. Barnhisel (ed.) Published by the American Society of Mining and Reclamation (ASMR), 3134 Montavesta Road, Lexington, KY 40502

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Conceptual Model and Pertinent Site Data

The Greens Creek Mine has a maritime climate with nearly 1,100 mm of annual precipitation. Tailings typically contain 10 to 18 % pyritic sulfur but also have abundant calcite (15 to 30 % by weight). Kinetic tests show that tailings will maintain an alkaline pH during tens to hundreds of years of oxidizing conditions, but could become acidic after very long-term exposure (Fig. 1).

The proposed cover to be placed at closure was designed to minimize infiltration of water and oxygen into the tailings. The cover (Unsaturated Soils Engineering 1999) will consist of 64 to 72 inches of cover material comprising 4 layers including (from top to bottom) growth media, a capillary break, a compacted barrier layer, and a basal capillary break (Fig. 2). Based on flux modeling (which used SoilCover, a 1-dimensional water and gas flux model), the net percolation through the cover was expected to average 165 mm/yr or about 15 % of annual precipitation. Oxygen flux was expected to decrease from about 300 to 500 g/m²/yr during operations to around 4 g/m²/yr after cover placement (Fig. 3). Consequently, the cover should reduce or eliminate the risk of acid generation.

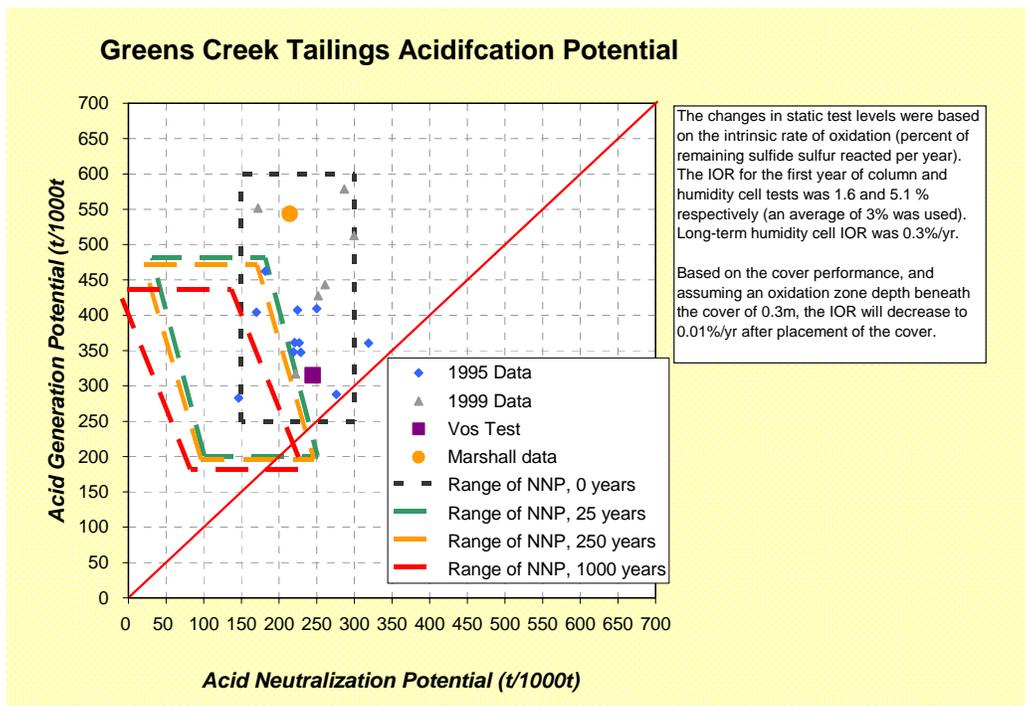
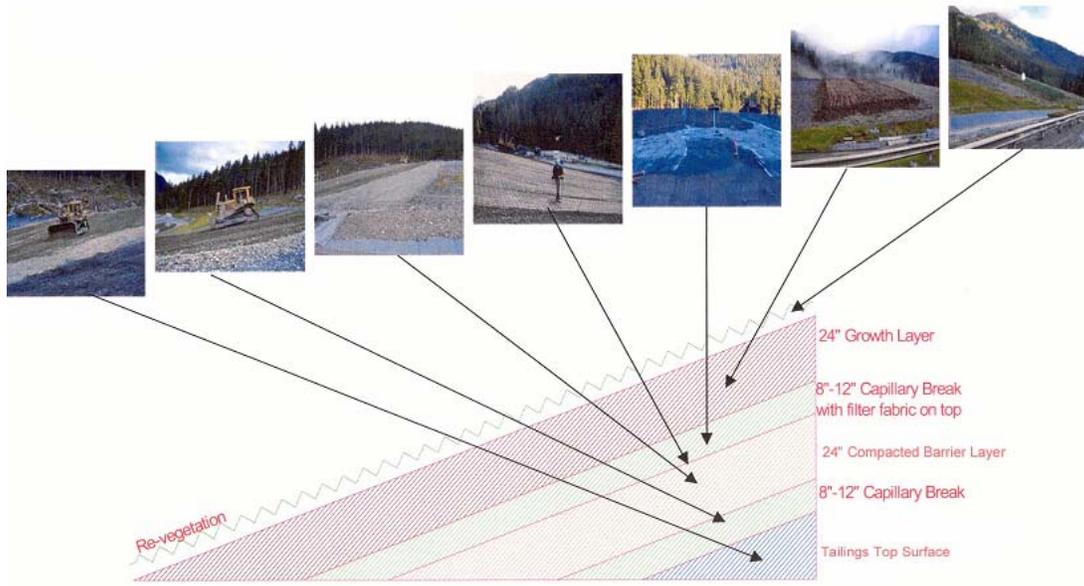


Figure 1. The potential range of acid generating and acid neutralizing potential of tailings is shown in the bounding box. The expected evolution through time is also shown which suggests that alkalinity will remain in place to sustain a neutral pH for up to 1,000 years.



Typical Four Layer Engineered Reclamation Cover

Figure 2. Schematic of the Greens Creek cover design.

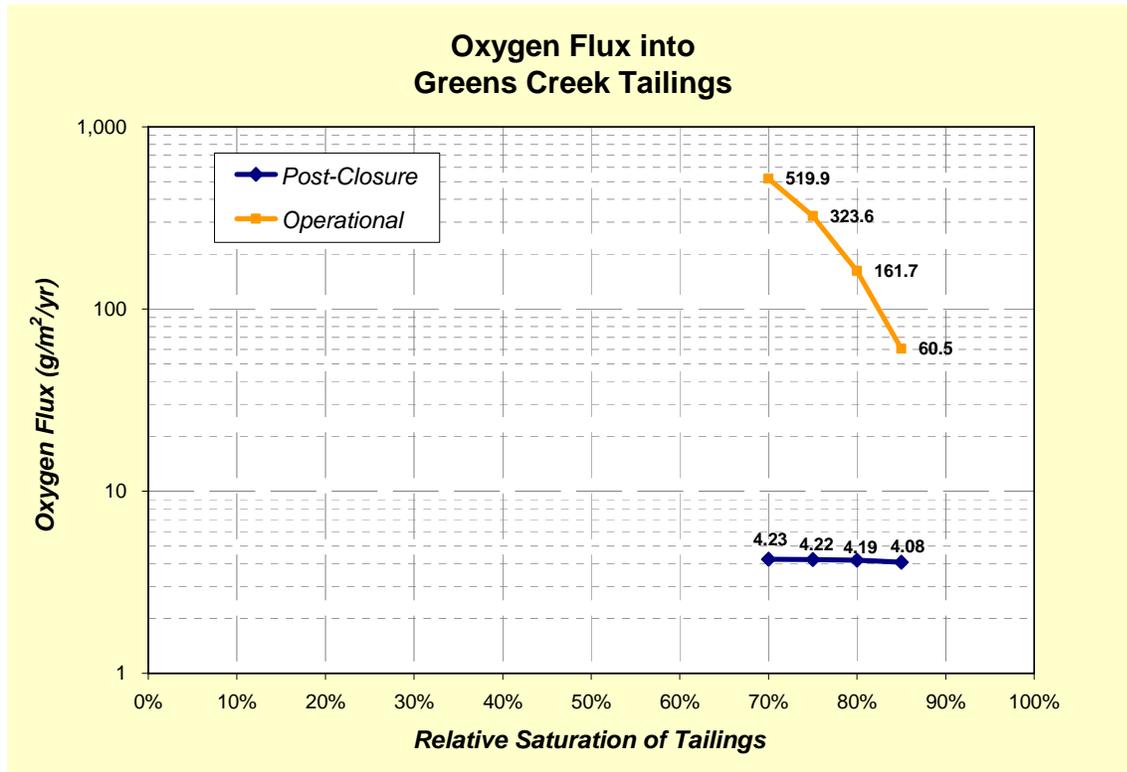


Figure 3. Calculated oxygen flux into the dry stack tailings during operations and post-closure after the cover is placed.

Tailings Contact Water Geochemistry

Interstitial water in contact with tailings in the oxidized portion of the pile contains elevated levels of metals, principally Zn. Deeper in the pile, reducing conditions are prevalent and Zn levels are very low, owing to SO_4^{-2} reduction processes. The solubility of SO_4^{-2} and metals within the tailings pile evolves along a complex reaction pathway as interstitial water migrates vertically in to the pile (Fig. 4). When placed, tailings contain process water with a slightly alkaline pH, around 0.1 mg/L Zn, moderate levels (e.g. 660 mg/L) of SO_4^{-2} and contain thiosalts such as thiosulfate (S_2O_3), which can release acidity during oxidation. In the near surface, as the tailings oxidize Zn and SO_4^{-2} levels may increase while pH remains near neutral owing to carbonate dissolution in the tailings. As water travels subsurface, the microbial oxidation of the dissolved organic carbon in the process water (or the refractory geologic carbon in the tailings solids) causes reducing conditions to develop. As some SO_4^{-2} is reduced to sulfide, the Zn levels decrease to near detection level and pH remains neutral. Consequently, as long as dissolved carbon is present, water flowing out of the pile is expected to remain low in Zn.

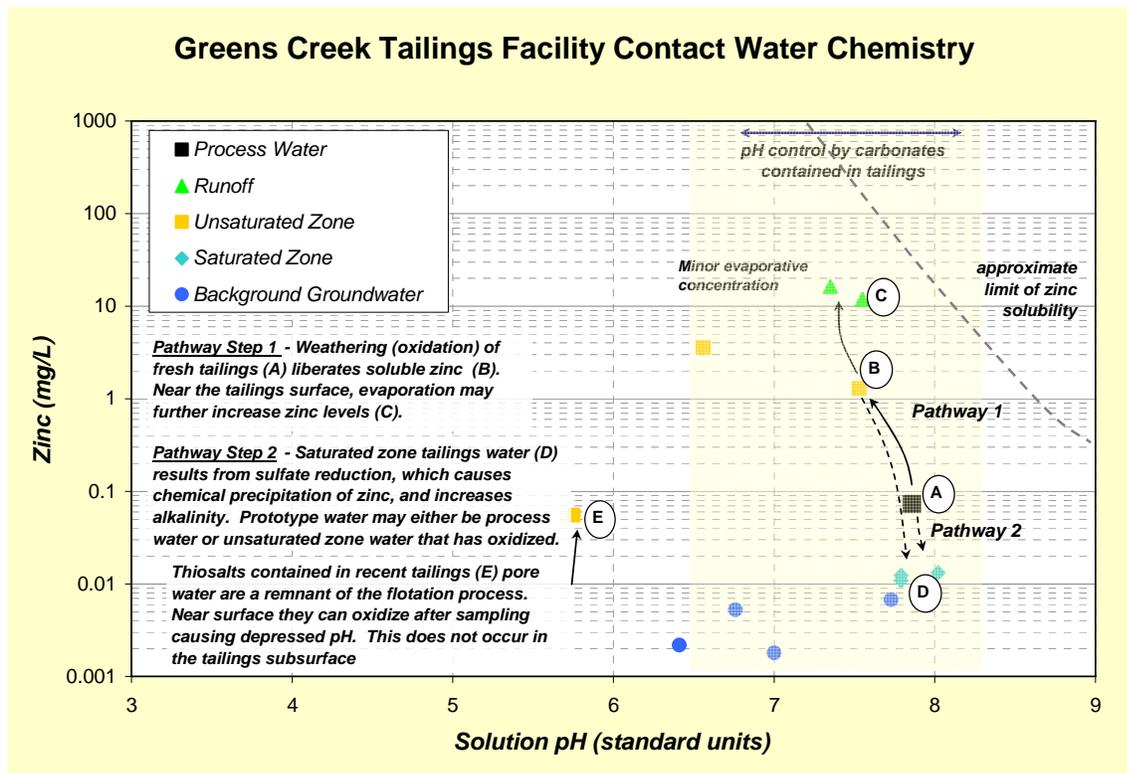


Figure 4. Potential mechanisms affecting zinc solubility in the Greens Creek tailings.

Stochastic Mass Load Model

A predictive mass load model was developed to simulate the geochemical characteristics of the oxidized and reduced portions of the pile, and predict how water and oxygen movement in the long-term may influence mass loads. The probabilistic model implemented as a @Risk[®] spreadsheet was used to evaluate various EIS design alternatives for the tailings expansion (Fig. 5). The model used a statistical distribution of input data (Table 1) to simulate water quality at three distinct locations in the tailings and receiving water environment including 1) interstitial water within the tailings, 2) water within the underdrain which consists of interstitial

water, groundwater and runoff, and 3) groundwater at a compliance point downgradient of the tailings where the underdrain water would mix with receiving localized groundwater recharge downgradient of the pile.

Kennecott Greens Creek Tailings Expansion Mass Load Model

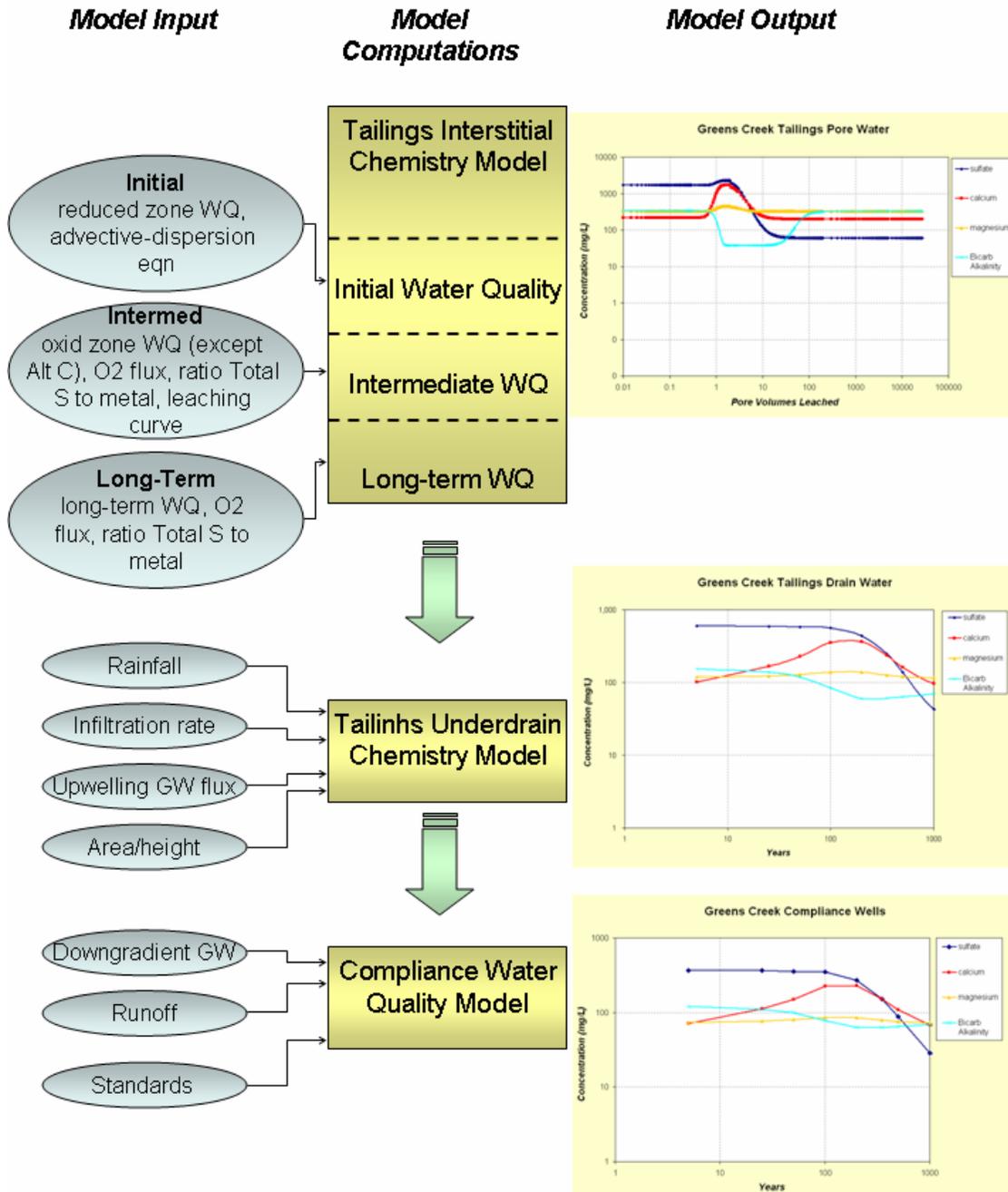


Figure 5. Conceptual model of the stochastic mass load model used to evaluate impacts from the Greens Creek Mine.

Table 1. Summary of model inputs.

Alternative Description	Proposed Action - place additional 6 million tons of tailings in expanded facility	Continuous carbonate addition	Use of organic carbon amendment as a continuous addition or as a veneer to promote sulfate reduction
Tailings Placement Area	24.8 ha	33.0 ha	25.2 ha
Chemistry of Tailings Pore Water			
<i>Initial tailings pore water (0 to 1 pore volume)</i>	Interstitial water represented by water samples obtained from deep piezometers and in which sulfate reduction is occurring.		
<i>Intermediate tailings pore water (1 to tens of pore volumes)</i>	Water from the upper oxidized portion of the pile will replace the reduced water as carbon supplies are exhausted. Water chemistry is best represented by the shallow lysimeters in tailings.	Water from the upper oxidized portion of the pile will replace the reduced water as carbon supplies are exhausted. Water chemistry is best represented by the shallow lysimeters in tailings.	Water will become completely reduced as the added carbon initiates sulfate reduction. Water chemistry is best represented by deep tailings piezometer samples in which sulfate reduction has occurred.
<i>Long-term tailings pore water (>tens of pore volumes)</i>	Water will retain the higher sulfate and trace element concentrations associated with the oxidized zone waters until the accumulated secondary minerals are rinsed from the tailings. Thereafter, concentrations will decline to lower equilibrium concentrations determined by the rate of long-term oxygen flux into the pile.	Similar to proposed action.	Water will remain reducing so that concentrations will change little. Some elements may decrease in concentration in response to decreased oxygen flux.
Hydrology Assumptions			
<i>Infiltration coefficient (operational)</i>	10 to 15 %, median 12 % of rainfall		
<i>Infiltration coefficient (post-closure)</i>	8 to 12 %, median 10 % of rainfall		
<i>Residual Water Content</i>	30 to 33.6%, median 31% volumetric		
<i>Oxygen flux (operational)</i>	Variable dependent on (and inverse to) water content ranging from 3 to 30 $\text{M}/\text{m}^2/\text{yr}$		
<i>Oxygen flux (closure)</i>	0.127 to 0.131 $\text{M}/\text{m}^2/\text{yr}$, median $\text{M}/\text{m}^2/\text{yr}$		
<i>Operating Period</i>	20 yrs		
<i>Oxygenated depth</i>	1 m		
<i>Dispersion coefficient</i>	0.02 unitless		
<i>Upwelling Groundwater</i>	0.72 to 5.0 L/s, median of 2.11 L/s with Pearson distribution		
Mixing Zone Assumptions			
<i>Area</i>	=500 m *1000 m		
<i>Recharge Rate</i>	10 % of rainfall		
<i>Groundwater Recharge (m^3/day)</i>	Area + Recharge Rate * Rain		
<i>Runoff</i>	Dependent on rainfall (45.4 % of days) and following a Pearson distribution		

Contact Water Chemistry

One of the key variables in the mass load model that affects long-term water quality is the water quality that emanates from the tailings pile. Tailings water quality is based in part on empirical tests of existing water quality, and also accounts for kinetic changes that may occur in the future. In the model, tailings water quality is determined separately for three time stages.

Initial Water Quality – The initial water quality draining out of the tailings after closure is expected to be the same as interstitial water currently held in the lower portion of the tailings. Water held in the pore space of deeper tailings has lower concentrations of key metals than occurs in the shallow oxidized portion of the tailings. This is due to SO_4^{-2} reduction, which tends to precipitate certain metals such as Zn, Ni and Se. Initial water quality emanating from the tailings is the same for each alternative. The initial stage is considered to persist until 1 pore volume of water has moved through the tailings pile.

Intermediate Water Quality – Once the water initially held in the tailings pore space has flowed out of the tailings mass and into the drain, the chemistry of the tailings water may change due to a change in the geochemical environment. For example, during operation of the tailings facility, organic carbon is added to the processing circuit. As the carbon decomposes, microbial SO_4^{-2} reduction begins. After the water held in the tailings is displaced by infiltration of meteoric water, the carbon source may be removed as well. Consequently, SO_4^{-2} reduction is expected to cease after one pore volume of water has flowed from the pile except when supplemental organic carbon is added. For other alternatives, the chemistry of the tailings pore water will gradually evolve toward that which is found in the shallower oxidized tailings.

Long-Term Water Quality – The long-term water quality represents the chemical equilibrium with the lower oxygen flux that is achieved by the engineered cover. Chemical equilibrium is not achieved until after the mass of stored oxidation products are removed (end of intermediate stage).

The model predicts the concentration of each constituent by assuming that the rate of oxygen flux (Fig. 3) controls the release of the soluble form of the constituent, and that the reaction products dissolve in the available water. The quantity of metal release based on sulfide oxidation rate was based on kinetic tests.

Mass Load Model Hydrology

The hydrology of the tailings facility considers upwelling groundwater intercepted by the drain layer, runoff from the facility, and seepage through the tailings. The model was calibrated using daily monitoring within the tailings water management system using hydrograph separation techniques to isolate groundwater inflow from runoff. The modeled hydrology closely simulated the range and distribution of groundwater and surface water flow from the tailings. The predicted hydrology was compared to measured hydrology using a duration curve, which depicts the distribution of instantaneous flow from the tailings facility from all sources (Fig. 6).

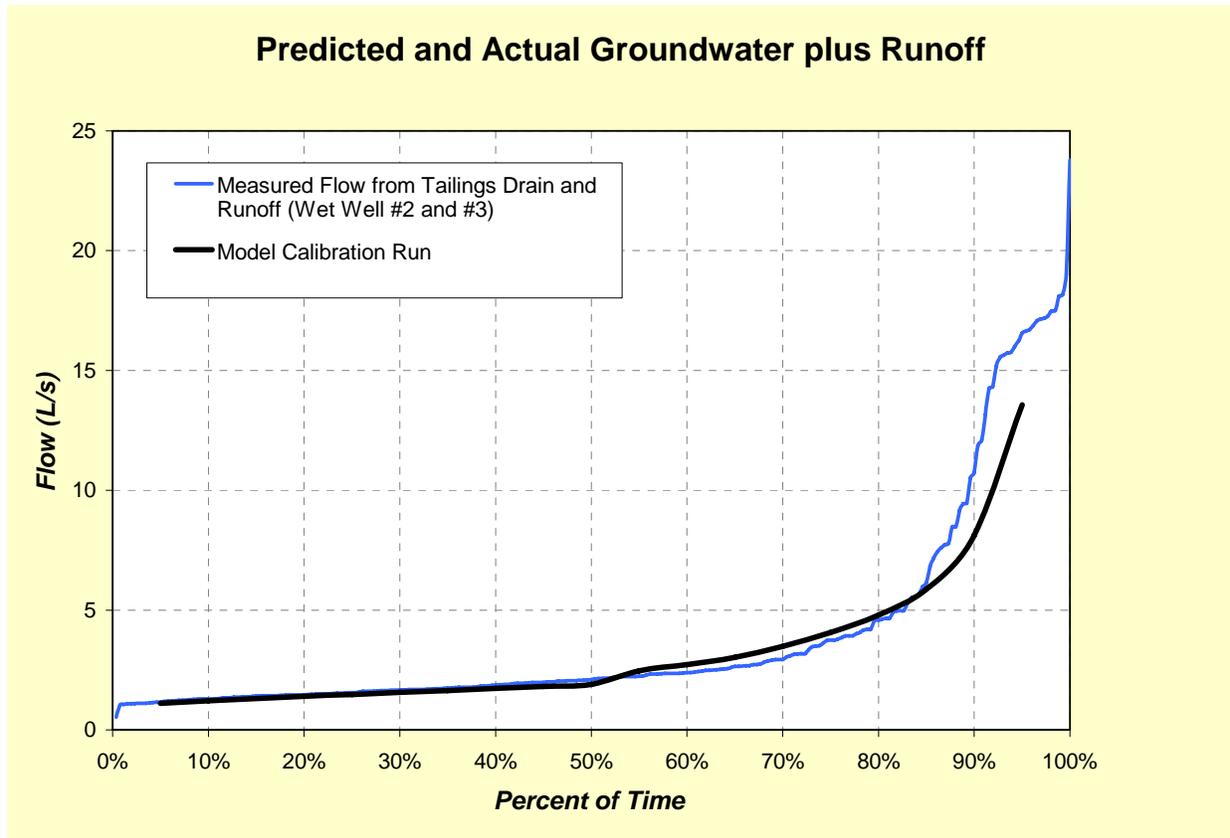


Figure 6. Duration curve comparing actual and predicted flow from groundwater and runoff from the tailings facility.

Model Chemical Calibration

The chemical response of the mass load model was calibrated by comparing constituent concentrations, measured within the tailings water management system to model-predicted concentrations. In a stochastic model, a range of chemical concentrations are calculated that correspond to the range of model inputs. Therefore, the highest and lowest measured concentration of each constituent was compared to the lowest probable (10 % probability), the highest probable (90 % probability), and median (50 % probability) concentrations derived from the mass load model (Fig. 7 to 9). The 10th to 90th percentile is shown as a shaded region while the median is a line.

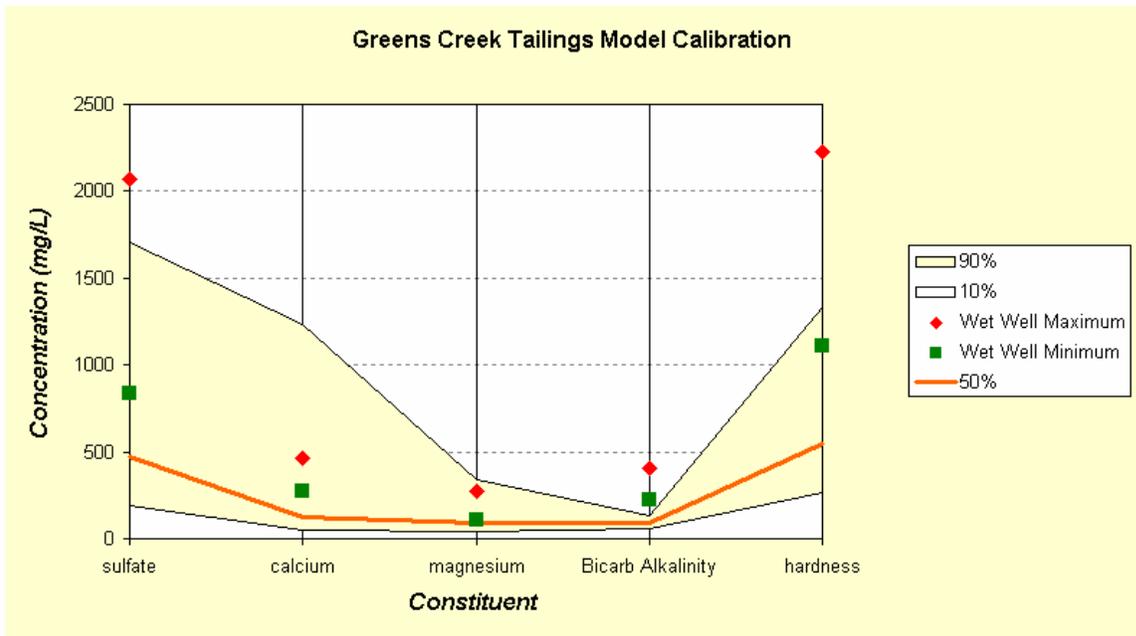


Figure 7. Predicted and actual concentrations of common ions in tailings contact water.

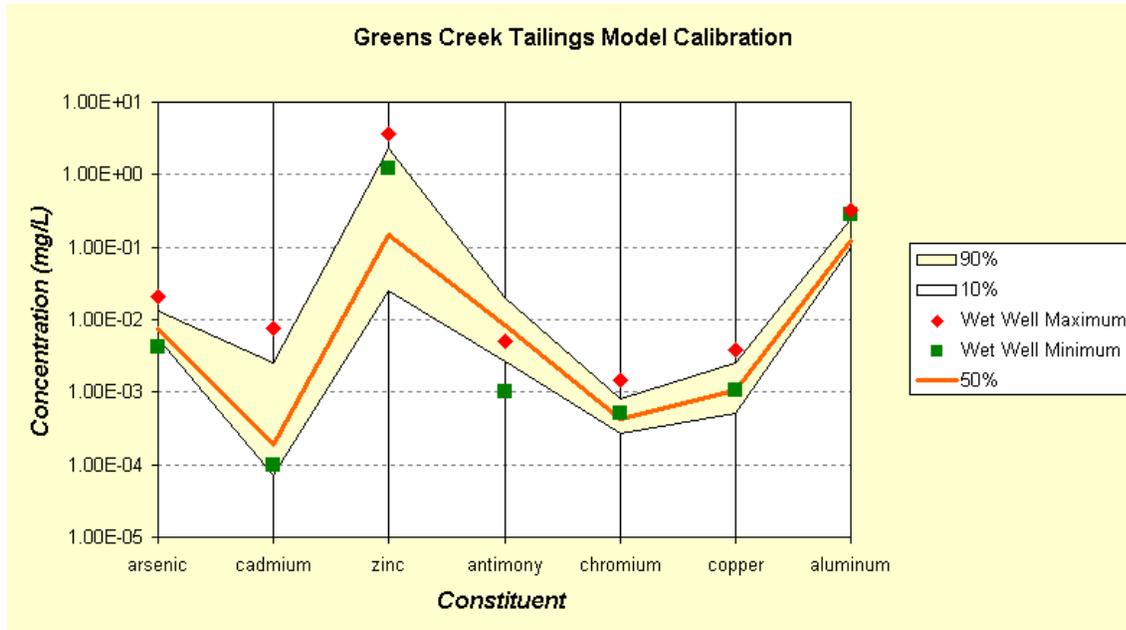


Figure 8. Predicted and actual concentrations of arsenic, cadmium, zinc, antimony, chromium, copper, and aluminum in tailings contact water.

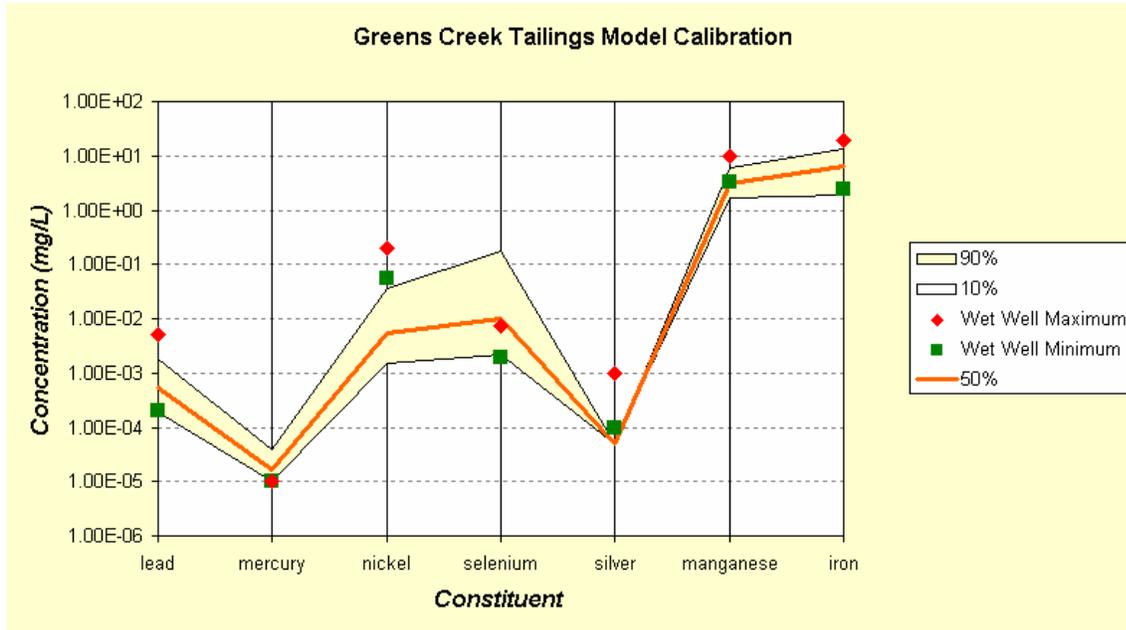


Figure 9. Predicted and actual concentrations of trace elements lead, mercury, nickel, selenium, silver, manganese, and iron in tailings contact water.

The model provided relatively close agreement with observed wet well chemistry with a few exceptions. Among common ions (Fig. 7) wet wells had higher SO_4^{-2} , HCO_3^- and hardness than predicted. The higher SO_4^{-2} is attributed to interaction of upwelling groundwater with the mineralized rock used to construct the drains. Oxidation of the drain material releases SO_4^{-2} , and probably also accounts for the higher than predicted Zn and Ni observed in wet wells (Fig. 8 and 9). Overall, the mass load model provided good agreement with the measured wet well chemistry.

Model Results and Impact Analysis

In the proposed action, tailings would be placed without chemical amendment. The model predicted (Fig. 10 and 11) that SO_4^{-2} would gradually decrease from around 300 mg/L to less than 100 mg/L after 500 years. Displacement of all of the interstitial water in the pile is very slow after cover construction, which accounts for the gradual change in water quality. Addition of organic carbon very slightly decreased the predicted SO_4^{-2} in solution while carbonate addition increased SO_4^{-2} owing to the expansion of the overall facility footprint.

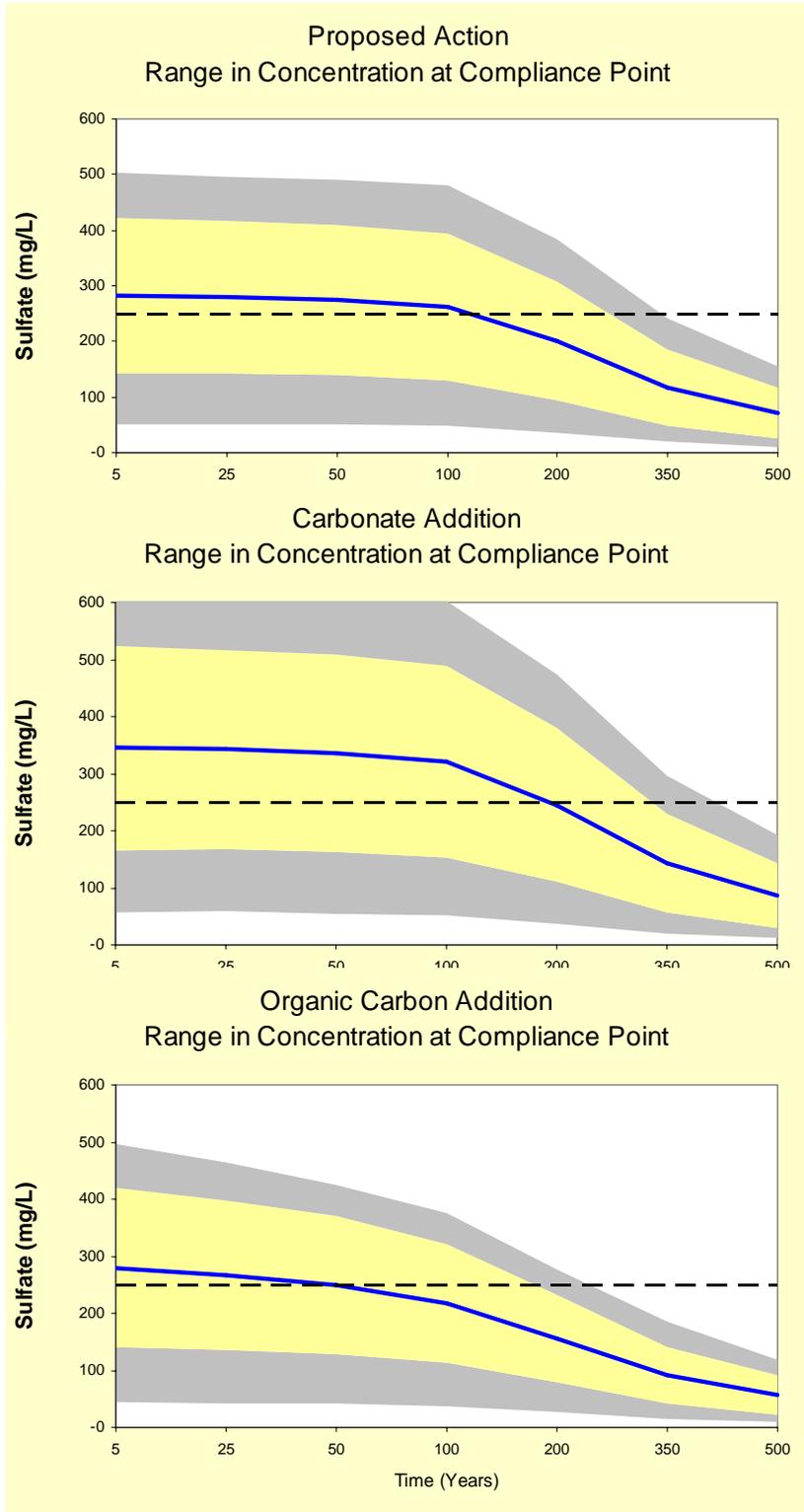


Figure 10. Range of predicted sulfate for placement of unamended, organic carbon, and carbonate amended tailings.

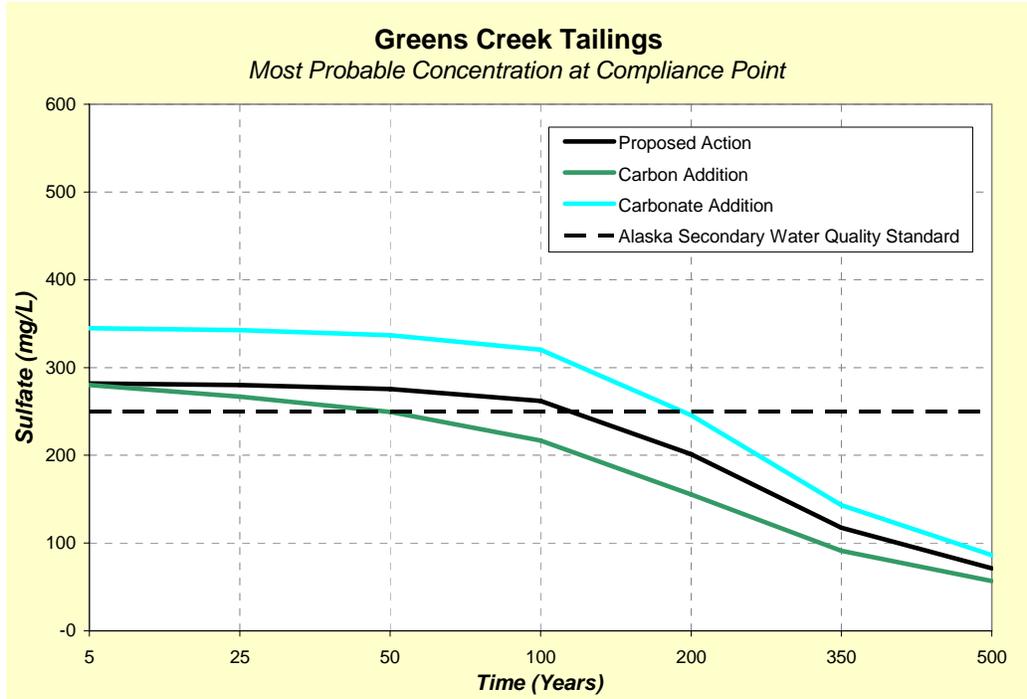


Figure 11. Expected case sulfate for placement of unamended, organic carbon, and carbonate amended tailings.

Predicted Zn concentrations (Fig. 12 and 13) were similar for the proposed action and the carbonate addition alternative because carbonates would not decrease existing levels of soluble Zn in neutral pH oxidized zones (about 0.5 mg/L). Organic carbon addition, however, was expected to greatly decrease soluble Zn, and was consequently selected as the preferred alternative. Studies are on-going to evaluate the mechanisms of SO_4^{-2} reduction in the dry stack tailings, to quantify the need for supplemental organic carbon addition to sustain SO_4^{-2} reduction post closure, and to determine the best means of organic carbon emplacement.

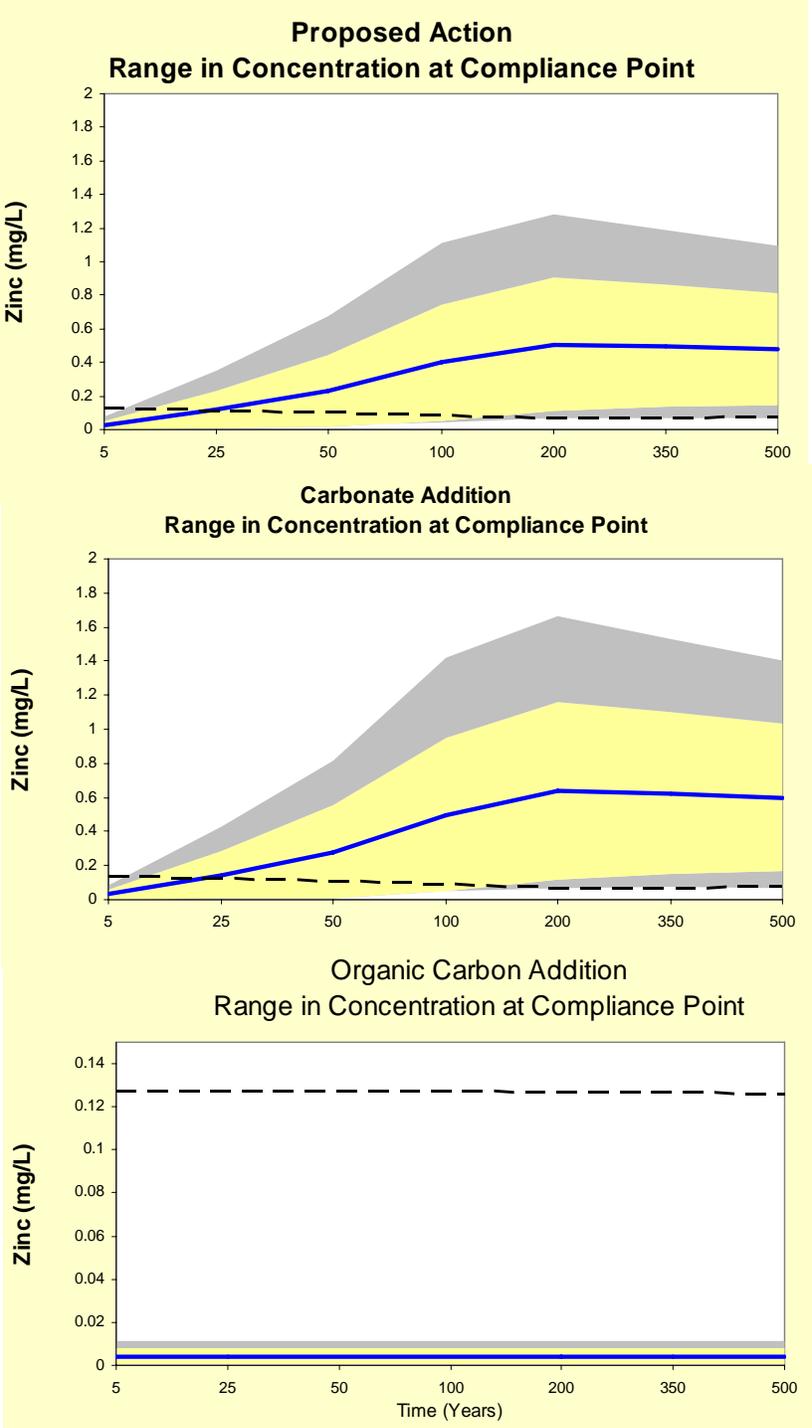


Figure 12. Range of predicted zinc for placement of unamended, organic carbon, and carbonate amended tailings.

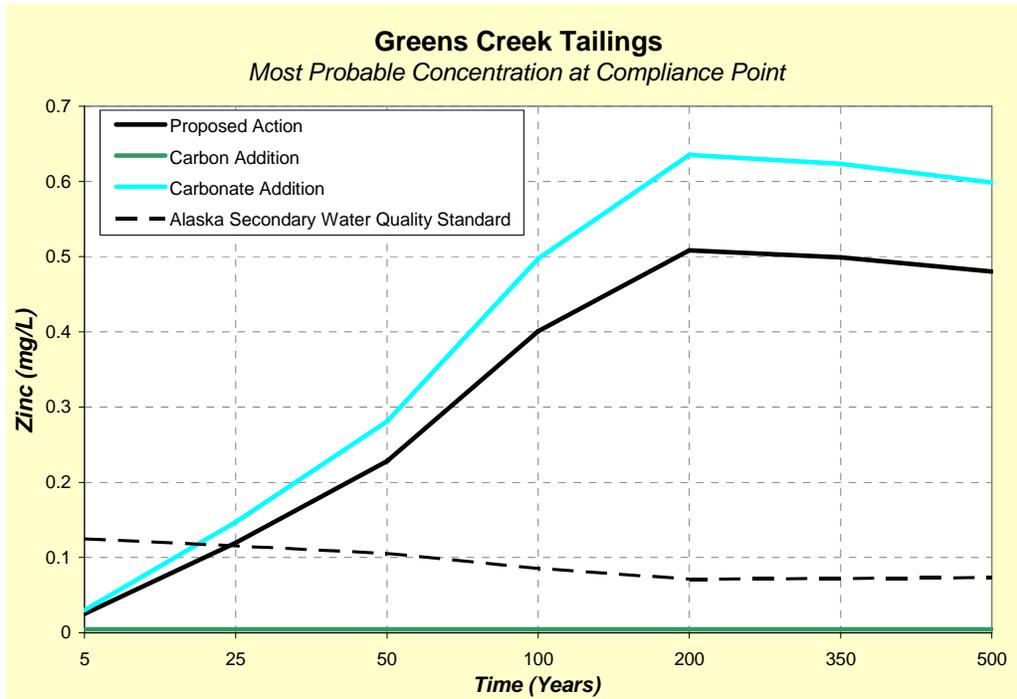


Figure 13. Expected case zinc for placement of unamended, organic carbon, and carbonate amended tailings.

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